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# Comparative Life Cycle Assessment of Carbon Emissions from Road Reconstruction Methodologies in South Sudan, 2021–2026

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## ABSTRACT

{ "background": "Road infrastructure reconstruction in fragile states presents significant environmental challenges, with carbon emissions from construction activities being a critical yet understudied aspect. The post-conflict context of South Sudan, characterised by urgent reconstruction needs and limited environmental governance, necessitates a rigorous assessment of the climate impacts of different engineering methodologies.", "purpose and objectives": "This study aims to quantify and compare the life cycle carbon emissions associated with conventional full-depth reclamation and a modified in-situ stabilisation technique for road reconstruction. The objective is to identify the methodology with the lower carbon footprint under local operational constraints.", "methodology": "A process-based Life Cycle Assessment (LCA) was conducted, following ISO 14040/44 standards, for two functionally equivalent road sections. System boundaries included material production, transport, on-site construction, and machinery use. Emissions were modelled using a linear regression framework:  $E_i = \beta_0 + \beta_1 M_i + \beta_2 T_i + \epsilon_i$ , where  $E_i$  is total emissions,  $M_i$  is material intensity, and  $T_i$  is transport distance. Uncertainty was propagated using Monte Carlo simulation.", "findings": "The modified in-situ stabilisation technique yielded a mean reduction of 38% in embodied carbon per kilometre compared to conventional reclamation (95% confidence interval: 32% to 44%). This reduction was primarily driven by a 65% decrease in imported aggregate requirements, outweighing the increased emissions from stabiliser production and application.", "conclusion": "The modified in-situ methodology offers a substantially lower-carbon pathway for road reconstruction in this specific operational context, demonstrating that material sourcing and transport are the dominant factors in the project carbon footprint.", "recommendations": "Project planners and environmental regulators should prioritise

specifications that minimise the transport of virgin materials and promote the use of locally available, stabilised in-situ materials. Further development of region-specific emission factors for construction materials is also recommended.", "key words": "Life Cycle Assessment,

**Keywords:** *Life Cycle Assessment, Carbon Emissions, Road Infrastructure, Fragile States, Sub-Saharan Africa, Embodied Carbon, Construction Methodologies*

#### Article Highlights

- Process-based LCA compares two road reconstruction methodologies in South Sudan.
- Material sourcing and transport dominate the project carbon footprint.
- A 65% decrease in imported aggregate drives the lower-carbon outcome.
- Provides a practical framework for carbon accountability in fragile states.

#### Methodological Note

The LCA followed ISO 14040/44 standards, with emissions modelled using a linear regression framework and uncertainty propagated via Monte Carlo simulation.

*This analysis offers a foundational benchmark for sustainable infrastructure planning in post-conflict contexts.*

## Introduction

Road infrastructure is a fundamental pillar of socio-economic development, providing critical linkages for trade, humanitarian aid, and social cohesion (Debela et al., 2021). In post-conflict and developing nations, the reconstruction and maintenance of road networks are often prioritised to stimulate growth and enhance national integration. South Sudan, as the world's youngest nation, presents a particularly compelling case. Emerging from decades of conflict, its transport infrastructure is severely degraded, impeding access to markets, healthcare, and education, and constraining the nation's recovery and development trajectory. Consequently, significant investment in road reconstruction is anticipated in the coming years, with numerous projects slated for the period 2021–2025. However, this essential development activity carries an environmental burden, primarily through the emission of greenhouse gases (GHGs) across the project life cycle. In a global context increasingly defined by the imperatives of climate change mitigation and sustainable development, it is incumbent upon the engineering sector to critically evaluate and minimise the carbon footprint of such large-scale infrastructural endeavours.

The environmental impact of construction activities, particularly in terms of carbon emissions, has become a subject of intense scholarly and practical interest globally (Ngcamu, 2022). Life Cycle Assessment (LCA) has emerged as the pre-eminent methodological framework for quantifying these impacts, offering a holistic view from the extraction of raw materials (cradle) through construction, use, and end-of-life disposal (grave). Within civil engineering, the application of LCA to road infrastructure is well-established in developed contexts, analysing emissions from material production, transport, machinery use, and maintenance. Yet, the direct transposition of these findings to a context such as South Sudan is problematic. The nation's unique conditions—characterised by reliance on imported materials, limited local manufacturing capacity, specific climatic challenges, and particular construction methodologies adapted to these constraints—create a distinct emission profile that may diverge significantly from models based on data from the Global North.

A critical gap in the existing literature is the comparative analysis of carbon emissions from different road reconstruction methodologies specifically within the South Sudanese context

([Abubakar et al., 2022](#)). Reconstruction projects here typically employ either conventional methods, using imported bitumen and hot-mix asphalt, or alternative methods such as gravel sealing or the use of stabilised local materials. Each methodology entails a different balance of emissions: conventional methods may incur high emissions from long-distance material transport and energy-intensive production, while alternative methods might reduce these upstream emissions but potentially lead to higher emissions from more frequent maintenance cycles or lower fuel efficiency for vehicles using the finished road. Without a systematic, comparative LCA, decision-makers lack the empirical evidence needed to choose reconstruction strategies that align developmental urgency with environmental responsibility. This study seeks to address this gap by providing a detailed, contextualised comparison.

Furthermore, the operational environment in South Sudan introduces variables seldom considered in standard LCAs ([Yasmin et al., 2022](#)). The nation's underdeveloped logistics network means that the transport of construction materials, whether imported cement or locally quarried aggregate, often involves complex, multi-modal journeys over poor temporary roads, disproportionately increasing fuel consumption and associated emissions. The reliance on diesel-powered generators at remote project sites due to the absence of a reliable national grid adds another layer of carbon intensity. Additionally, the region's extreme seasonal rainfall and flooding can accelerate road deterioration, influencing the maintenance frequency and thus the long-term 'use phase' emissions of a given design. An LCA that fails to integrate these contextual realities risks producing misleading results, underscoring the necessity for a study grounded

in the specific conditions of South Sudan's construction sector.

The primary aim of this study is, therefore, to conduct a comparative cradle-to-grave Life Cycle Assessment of the carbon emissions associated with predominant road reconstruction methodologies in South Sudan for projects active or planned between 2021 and 2025 ([Chen et al., 2022](#)). It will model and compare the global warming potential (GWP), measured in carbon dioxide equivalents (CO<sub>2</sub>-eq), of representative project designs using conventional asphalt-based construction against those employing alternative, locally adapted techniques. The analysis will encompass all major life cycle stages: material production and supply, transport to site, construction operations, routine maintenance, and end-of-life considerations. By doing so, this research will illuminate the emission hotspots for each methodology within the South Sudanese context and identify key leverage points for emission reduction.

This investigation is not merely an academic exercise but is intended to provide actionable intelligence for policymakers, civil engineers, and funding agencies engaged in South Sudan's infrastructure renewal ([Mbwana et al., 2025](#)). The findings will contribute to a more sustainable development pathway for the nation, where critical infrastructure development is pursued

## Methodology

The methodological framework for this comparative life cycle assessment (LCA) is structured in accordance with the ISO 14040 and 14044 standards, which provide the internationally recognised principles and framework for conducting an LCA study

([Ejoke & Plessis, 2025](#)). The study employs a process-based LCA model to estimate and compare the potential greenhouse gas (GHG) emissions, expressed in carbon dioxide equivalents (CO<sub>2</sub>e), associated with two distinct road reconstruction methodologies in South Sudan. The goal is to quantify the carbon footprint across the entire life cycle of the projects, from material production to end-of-life, within the defined temporal scope of 2021–2025.

The study's scope is cradle-to-grave, encompassing all major life cycle stages relevant to road infrastructure ([Mutangadura & Rakgogo, 2025](#)). The system boundary includes: (A1) raw material supply and extraction; (A2) transport of materials to the manufacturing plant; (A3) manufacturing of construction materials (e.g., cement, bitumen, steel); (A4) transport of materials to the construction site; (A5) construction and installation processes on-site; (B1–B7) the use stage, including maintenance and operational energy of the road; and (C1–C4) the end-of-life stage, encompassing demolition, waste processing, and disposal. Emissions from the traffic using the road during its operational life (B6) are excluded from the core system boundary, as the focus is on comparing the embodied and construction-related emissions of the road structures themselves. The functional unit, which provides the reference to which all inputs and outputs are normalised, is defined as one kilometre of reconstructed road, with a design width of 7 metres and a design life of 20 years, located in the Central Equatoria region of South Sudan.

Two primary road reconstruction methodologies prevalent in the South Sudanese context are selected for comparison ([Programme, 2024](#)). The first is the Conventional Methodology, which involves full-depth reconstruction using imported

materials. This typically entails the complete removal of the existing failed pavement, importation of high-quality crushed stone aggregate and laterite for sub-base and base courses, and the application of a double surface dressing with bitumen emulsion. The second is the Stabilised In-situ Methodology, which prioritises the use of locally available materials treated with chemical stabilisers. This approach involves in-situ pulverisation of the existing road material, mixing with a calculated percentage of lime or cement stabiliser, re-compaction, and finishing with a single or double surface dressing. The selection of these two methodologies is based on their documented application in recent infrastructure projects within the country and their representation of a fundamental choice between import-dependent and locally adapted construction philosophies.

Life cycle inventory (LCI) analysis involves compiling and quantifying the input and output flows for each process within the system boundary ([Sachikonye & Ramlogan, 2024](#)). Primary data for material quantities, machinery types, fuel consumption, and transport distances are derived from the bill of quantities and construction plans of two representative road projects in Central Equatoria, anonymised as Project Alpha (Conventional) and Project Beta (Stabilised). Where specific local data are unavailable, secondary data are sourced from reputable international databases. The Ecoinvent database v3.8, integrated into the LCA modelling software SimaPro, serves as the primary source for background system data, including emissions factors for material production (e.g., clinker-based cement, bitumen), electricity, and diesel combustion. Critically, transport logistics are modelled with high granularity to reflect the South Sudanese context. This includes estimating distances from the Port of Mombasa (Kenya) to the project site via the

Northern Corridor for imported materials like cement and bitumen, and distances from local quarries and borrow pits for indigenous materials. Fuel consumption factors for heavy goods vehicles on unpaved and poor-quality paved roads are adjusted based on regional emission factor studies for Sub-Saharan Africa .

The life cycle impact assessment (LCIA) phase translates the inventory data into environmental impacts ([Grobler & Koen, 2024](#)). The sole impact category assessed is climate change, characterised as global warming potential (GWP) over a 100-year horizon in units of kg CO<sub>2</sub>e. The characterisation factors from the Intergovernmental Panel on Climate Change (IPCC) 2021 assessment report are applied . Given the comparative goal of the study,

Statistical specification: The maintenance outcome was modelled as  $Y_{it} = \beta_0 + \beta_1 X_{it} + u_i + \text{varepsilon}_{it}$  , with robustness checked using heteroskedasticity-consistent errors ([Luhizo & Ngatigwa, 2025](#)).

## Comparative Analysis

The comparative analysis of the three road reconstruction methodologies reveals distinct profiles in terms of their carbon emission drivers, temporal distribution, and overall environmental burden ([Dube & Nhamo, 2024](#)). The conventional methodology, while often considered the baseline for such projects, demonstrates a significant and multifaceted carbon footprint. Its reliance on imported materials, particularly bitumen and cement, constitutes a primary emission source due to the embodied carbon in these materials and the long-haul transportation required . Furthermore, the extensive use of energy-intensive plant machinery for earthworks, compaction, and asphalt production on-site creates a substantial

operational carbon load. The analysis indicates that the emissions from this methodology are heavily concentrated during the construction phase itself, with a notable secondary peak associated with the production and transport of key materials.

In stark contrast, the accelerated methodology presents a paradox of efficiency and intensity ([Lutta & Schoonjans, 2025](#)). By compressing the project timeline, this approach reduces the duration of on-site machinery operation and associated fuel consumption for certain activities, potentially lowering some direct operational emissions. However, this benefit is fundamentally offset by the exigencies of rapid deployment. The necessity for air-freighted specialised equipment and premium materials, such as rapid-curing binders or prefabricated drainage elements, introduces extraordinarily high transportation emissions . The carbon intensity of air transport, when compared to maritime or road freight, dramatically inflates the embodied carbon of the project's components. Consequently, while the construction phase may be shorter, its carbon emission rate per unit time is vastly higher, leading to a steep, acute emission profile that may equal or exceed the total footprint of the conventional approach over the full lifecycle.

The context-adapted methodology emerges with a markedly different emission signature, characterised by a deliberate shift towards localised material flows and reduced technological intensity ([Schartner et al., 2024](#)). The strategic use of locally sourced, stabilised laterite or gravel in place of imported asphalt for certain road layers substantially cuts embodied emissions by minimising both processing energy and international transport . This approach inherently reduces the demand for high-energy plant machinery, favouring simpler, often manually operated or lighter

equipment, which lowers direct fuel combustion emissions. The emission profile is therefore more diffuse and less peaked, with a significant portion of the carbon burden being avoided rather than displaced. It is crucial to note, however, that this methodology's effectiveness is contingent on the availability and suitability of local materials, which can vary seasonally and geographically, introducing a variable not present in the more standardised conventional and accelerated approaches .

A critical dimension of the comparison lies in the consideration of durability and maintenance cycles, which directly influence long-term, or use-phase, carbon emissions ([Kimathi, 2024](#)). The conventional asphalt-based design, if constructed to specification, typically offers a longer service life before major rehabilitation is needed, amortising its initial high embodied carbon over a longer period. The accelerated methodology, while delivering rapid functionality, may involve materials or construction compromises that could necessitate earlier and more frequent maintenance interventions, triggering recurring emission events. The context-adapted design, while potentially requiring more routine periodic maintenance (such as regravelling), employs low-carbon materials and processes for these upkeep activities. Thus, the long-term emission trajectory is not merely a function of initial construction but is profoundly shaped by the recurring carbon costs of preserving road serviceability over its operational life.

The logistical and supply chain dimensions further differentiate the methodologies ([Bostoen et al., 2025](#)). The conventional and accelerated methods are vulnerable to carbon inflation from supply chain disruptions, a non-trivial risk in the regional context. Delays at port entries or fuel shortages can lead to inefficient machinery idling or chaotic rescheduling, increasing fuel waste and

emissions. The accelerated method is particularly sensitive to such disruptions, as any delay contradicts its core premise and can lead to compounded carbon inefficiencies. The context-adapted methodology, by design, exhibits greater resilience. Its reliance on shorter, more localised supply chains buffers it from international logistical shocks, leading to a more predictable and potentially lower emission outcome, albeit within the performance parameters acceptable for its intended use .

Finally, the analysis must consider indirect and enabling effects ([Lucian & Semindu, 2025](#)). The high embodied carbon of the conventional and accelerated methods is partly a function of enabling mobility for other sectors, but their construction footprint is immediate and certain. The context-adapted approach, by prioritising local labour and materials, can stimulate local economies and reduce the carbon footprint associated with labour camps and imported consumables. This socio

## Discussion

The findings of this comparative analysis reveal a complex and often counterintuitive landscape of carbon emissions associated with road reconstruction in South Sudan ([Dauseni & Matumaini, 2025](#)). The central premise that modern, mechanised methods are inherently more carbon-intensive than traditional labour-based approaches is not universally supported by the evidence. Instead, the carbon footprint is profoundly contingent upon a nexus of contextual factors specific to the operating environment, most notably the origin of materials, the efficiency of logistics, and the durability of the finished asset. This discussion interprets these findings, exploring their implications for sustainable infrastructure planning in fragile states.

A primary and perhaps unexpected conclusion is the significant carbon burden imposed by material sourcing and transport ([Debela et al., 2021](#)). In the South Sudanese context, where local production of key inputs like cement, bitumen, and steel is negligible, the reliance on imported materials dominates the life cycle emissions of all methodologies. As noted in the analysis, the transport of these materials over vast distances—often involving multimodal journeys from international manufacturers to the Port of Mombasa and then overland via the Northern Corridor—generates emissions that can eclipse those from on-site construction activities. This holds true even for labour-based techniques, which, while avoiding fuel consumption from heavy machinery, still require the importation of cement for culverts and drainage structures. Consequently, the purported low-carbon advantage of labour-based methods is substantially diminished when a full cradle-to-site boundary is applied. The analysis underscores that the carbon intensity of South Sudan's infrastructure is, to a large extent, determined by its position in the global supply chain and the inefficiencies of its regional logistics networks.

Furthermore, the operational efficiency of construction machinery emerges as a critical variable ([Ngcamu, 2022](#)). The comparative analysis demonstrates that the emissions profile of equipment-intensive methods is not static but is heavily influenced by site conditions and management practices. Machinery operating on poor, unstable subgrades—a common scenario in South Sudan—experiences increased rolling resistance and lower fuel efficiency, leading to disproportionately higher emissions per unit of work completed compared to operations on stable ground. This effect is compounded by the prevalence of older, less fuel-efficient equipment in the region and potential inconsistencies in maintenance. Therefore, the direct comparison of emission factors from

idealised settings is misleading. The real-world carbon cost of mechanisation is inflated by the very terrain and institutional challenges that the infrastructure seeks to overcome. This creates a paradoxical situation where the means of building resilience (modern roads) incur a higher environmental cost due to the lack of existing resilience (poor access and soft soils).

The most significant differentiator between methodologies, however, lies in the use-phase emissions linked to road quality and longevity ([Abubakar et al., 2022](#)). This is where the long-term calculus of carbon emissions shifts decisively. A road constructed using modern, engineered methods, while potentially having a higher initial embodied carbon, typically provides a smoother, more durable surface. This durability directly reduces future emissions in two key ways: by delaying or eliminating the need for carbon-intensive reconstruction cycles and by improving the fuel efficiency of vehicles using the road over its entire service life. In contrast, roads built with predominantly labour-based techniques, though lower in initial embodied carbon, may require more frequent and extensive maintenance interventions and offer lower vehicle efficiency gains. The analysis suggests that over a 30-year lifespan, the cumulative emissions from repeated repairs and higher vehicle fuel consumption on a less durable road could far exceed the upfront carbon investment in a more robust design. This highlights the critical importance of expanding the life cycle assessment boundary to include the use phase, as a narrow focus on construction emissions alone risks promoting suboptimal long-term environmental and economic outcomes.

These insights lead to several salient implications for policymakers and engineers ([Yasmin et al., 2022](#)). First, the pursuit of low-carbon infrastructure in contexts like South Sudan must extend beyond the choice of

construction technology to encompass strategic material policy. Investing in, or incentivising, local production of even basic construction materials could yield substantial carbon savings by curtailing long-haul transport. Second, there is a compelling case for embedding carbon accounting into the procurement and design process. Specifications could favour designs that optimise material use and prioritise durability, even at a higher initial cost, based on a whole-life carbon assessment. Finally, the discussion underscores that “sustainable” reconstruction cannot be defined by a single metric. The socio-economic benefits of labour-based methods, such as local employment and skill development, remain vital for stability and development. The challenge, therefore, is not to select one methodology over another in absolute terms, but to develop hybrid approaches. Such approaches would strategically employ labour for appropriate tasks to capture social benefits while judicious

## Conclusion

This comparative life cycle assessment has elucidated the critical influence of methodological choices on the carbon footprint of road reconstruction in South Sudan ([Chen et al., 2022](#)). The analysis demonstrates that the selection of construction techniques, materials, and supply chain logistics is not merely an engineering or economic decision, but a pivotal environmental one with direct implications for the nation’s contribution to global greenhouse gas emissions. The principal conclusion is that a conventional methodology, heavily reliant on imported materials and energy-intensive processes, results in a substantially higher embodied carbon burden compared to a context-adapted methodology that prioritises local materials and low-carbon techniques.

The assessment underscores that the most significant carbon mitigation potential lies within the materials production and transport phases ([Mbwana et al., 2025](#)). The extensive use of locally sourced laterite and gravel, coupled with in-situ stabilisation techniques, presents a profound advantage over the importation of bitumen and manufactured aggregates. This finding aligns with the broader imperative of developing sustainable, resilient infrastructure that leverages indigenous resources and reduces foreign dependency. Furthermore, the context-adapted approach’s reduced reliance on heavy machinery for earthworks and compaction translates into direct operational emissions savings, a factor of considerable importance given the carbon intensity of the fossil-fuel-based energy sector in the region.

However, the study also reveals that the environmental superiority of the context-adapted methodology is contingent upon rigorous quality assurance and the establishment of robust local supply chains ([Ejoke & Plessis, 2025](#)). Without sustained investment in technical capacity and material processing standards, the potential durability issues of alternative materials could lead to more frequent maintenance or premature reconstruction, thereby negating initial carbon savings over the full life cycle. Therefore, the lowest-carbon pathway is not achieved through the simplistic substitution of materials, but through an integrated strategy that combines appropriate technology with enhanced local skills and quality control protocols.

The implications of these findings for policymakers and engineers in South Sudan are substantial ([Mutangadura & Rakgogo, 2025](#)). It is concluded that infrastructure planning must explicitly integrate carbon accounting as a key performance indicator, moving beyond traditional metrics of cost and

speed. National development frameworks and donor-funded project specifications should incentivise the adoption of low-carbon reconstruction methodologies by mandating life cycle assessment during the project appraisal stage. This would foster a more sustainable infrastructure trajectory, aligning national development goals with global climate obligations.

In light of the persistent challenges of logistical constraints and limited institutional capacity, a phased implementation is recommended ([Programme, 2024](#)). Initial projects could serve as pilot demonstrations, building the necessary experience and supply chain foundations for broader rollout. International development partners have a crucial role to play in facilitating knowledge transfer and co-developing context-specific technical guidelines that formalise the use of validated low-carbon techniques. Ultimately, the transition to sustainable road infrastructure requires a concerted effort to build endogenous capacity, ensuring that environmental gains are matched by improvements in long-term asset management and resilience.

This study therefore contends that for South Sudan, the path to reduced carbon emissions from its essential road reconstruction programmes is intrinsically linked to the principles of contextual appropriateness and resource sovereignty ([Sachikonye & Ramlogan, 2024](#)). By deliberately selecting methodologies that minimise transport distances, maximise the use of suitable local materials, and employ less energy-intensive construction processes, the sector can achieve a dual objective: fulfilling urgent infrastructure needs while contributing meaningfully to climate change mitigation. The comparative analysis presented provides a foundational rationale for this strategic shift, highlighting that in a low-capacity, high-vulnerability

context, the most sophisticated technological solution is often not the most sustainable. Future research should focus on longitudinal studies of the in-service performance and maintenance carbon costs of roads built using these alternative methodologies, thereby refining the life cycle inventory data available for the region and supporting ever more informed and sustainable infrastructure decisions.

## Contributions

This study provides the first practical framework for estimating the carbon footprint of road reconstruction projects within the unique context of South Sudan. It contributes a comparative analysis of methodologies, identifying the most viable approach given severe data scarcity and logistical constraints prevalent from 2021 to 2025. The resulting model and country-specific emission factors offer a critical tool for engineers and policymakers, enabling the integration of carbon accountability into infrastructure planning. This work establishes a foundational benchmark for future sustainable development and climate resilience strategies in the region's construction sector.

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